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Innovations in oral pulmonary and targeted drug delivery technologies

Ashutosh Sengar

Department of Pharmaceutics, S.R. Group of Institutions, Jhansi, Uttar Pradesh, India

ABSTRACT

The progress in pharmaceutical sciences has had a remarkable effect in that the traditional dosage forms are now used to manufacture sophisticated, patient-oriented delivery platforms. For instance, the review looks at the innovations across oral, pulmonary, and targeted delivery systems for drugs comprehensively, and importantly, it discusses formulation strategies, mechanistic insights, and the therapeutic relevance of these innovations. Among these modern drug delivery systems are chewable tablets, fast-dissolving films, effervescent, and controlled-release formulations, which all demonstrate their potential for increasing the bioavailability, patient adherence, and clinical efficacy significantly.

Drug delivery systems through pulmonary and nasal passages are direct, non-invasive routes for both localized and systemic therapy that employ nanoformulations and inhalation technologies to their advantage in the areas of pharmacokinetics and patient outcomes. At the same time, lipid-based carriers such as liposomes and nanostructured lipid systems have transformed drug encapsulation and targeting accuracy in, for example, cancer therapeutics and controlled release applications.

The soon to come self-powered and pinpointed delivery technologies are the frontier in personalized medicine area using body signals and smart material design for release that is both automatic and site-specific. The blend of these various disciplines marks a turning point in treatment paradigms, from conventional medications to smart, effective, and patient-adaptive therapeutic systems.

The aim of this article is to bring forth an integrative viewpoint that ties together basic science, formulation development, and translational applications, thereby assisting the worldwide effort in finding the most efficient, next-generation drug delivery solutions.

KEY WORDS

Drug delivery systems; Lipid-based nanocarriers; Pulmonary delivery; Oral dosage innovations; Targeted therapeutics

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Introduction

Drug delivery systems have been the driving force behind the revolution in administering therapeutic agents by improving their efficacy, patient compliance, and targeted action. The continuous innovation in the area has led to the introduction of specialized delivery routes like naso-pulmonary, oral, and nanocarrier-based systems that are designed to counteract biological barriers and increase bioavailability [1].

The adoption of modern approaches has transitioned from traditional dosage forms to highly engineered nanocarriers and rapidly dissolving platforms that ensure accurate drug release and site-specific delivery [2]. These new systems are the link connecting classical pharmaceutical formulations and next-generation nanotechnologies, thus guaranteeing better therapeutic performance and smaller systemic side effects [3].

One of the most important advantages of nanocarrier-based technologies is their flexibility regarding drug encapsulation and sustained release, thus making a significant contribution to personalized and precision medicine [3]. At the same time, new research is investigating delivery methods that are self-powered and targeted, which would operate like physiological stimuli, thus offering autonomous and intelligent therapeutic responses [4].

In addition to that, controlled drug delivery is still an important part of the pharmaceutical industry innovating, since it not only makes the release of the drug very predictable but also allows for infrequent dosing and increases the patient's adherence. The use of new materials, responsive polymers, and nanostructures is continually pushing the boundaries of therapeutic delivery for various clinical applications [5].

Oral Drug Delivery Systems

Chewable tablets

Chewable tablets are one of the kinds of medicines that are very much liked by patients. It is a dosage form that has been specifically developed to help improve the compliance of patients, especially the young and the old ones. The manufacturing of chewable tablets involves considering certain factors like taste masking, mechanical strength, and disintegration behavior to assure both efficacy and acceptability [6]. These types of tablets are a great help for those people who have a problem with swallowing since they provide the same benefits as good old-fashioned tablets in terms of bioavailability and stability, but with less trouble.

Technology related to chewable tablets has changed a lot in recent years, and one of the main trends has been the use of new excipients and flavouring systems to enhance the mouthfeel and palatability. The development of powerful compression machines and of the microencapsulation process has also made it possible to have an even drug distribution, controlled release, and the moisture-sensitive drugs getting

***Correspondence:** Dr. Ashutosh Sengar, Department of Pharmaceutics, S.R. Group of Institutions, Jhansi, Uttar Pradesh, India
email: ashutoshsengar26567@gmail.com

better [7]. Moreover, the latest trends are making the combination of the beauty of the product with the functional design, like the use of colorants and natural sweeteners to elevate the user acceptability [8] (Table 1).

The clinical importance of chewable tablets has been and still is very great, and the need to have the tablets ready for quick dispensing and of liquid therapies requiring rapid onset of action are the main reasons for that. Better formulation strategies are the ones that get the dosing and the bioavailability right while being easy for the consumer [9]. In conclusion, these developments have made chewable tablets multi-purpose, reliable, and even more attractive oral drug delivery, thus allowing pharmaceutical precision still balancing with patient comfort [6–10].

Table 1. Chewable tablets as an oral drug delivery system.

Subtopic	Description	Key Advantages	References
Purpose & Patient Compliance	Chewable tablets are designed to enhance compliance, particularly for paediatric, geriatric, and dysphagic patients. They provide similar bioavailability and stability as conventional tablets.	Easy to swallow, patient-friendly, suitable for populations with swallowing difficulties.	[6, 10]
Formulation Considerations	Development focuses on taste masking, mechanical strength, and disintegration behaviour to ensure acceptability and therapeutic performance.	Improved palatability, enhanced acceptance, optimized effectiveness.	[6]
Technological Advancements	Use of new excipients, advanced flavouring systems, improved compression machinery, and microencapsulation techniques for uniformity and stability.	Better drug distribution, controlled release potential, improved protection for moisture-sensitive drugs.	[7]
Aesthetic & Functional Design Enhancements	Incorporation of natural sweeteners, colorants, and improved mouthfeel.	Greater user acceptability, more appealing dosage forms.	[8]
Clinical Importance	Useful for rapid onset therapies and situations requiring fast dispensing. Formulations aim to balance bioavailability with user convenience.	Suitable for immediate-release applications, improved dosing accuracy, high patient satisfaction.	[9]
Overall Significance	Chewable tablets have evolved into reliable, multipurpose delivery systems that combine pharmaceutical precision with patient comfort.	Versatile, stable, patient-centred oral dosage form.	[6–10]

Fast dissolving films and oral strips

Fast-dissolving films (FDFs) and oral strips are among the modern dosage forms that disintegrate instantly when they meet saliva, giving a whole lot of advantages as a non-invasive method for drug administration that does not require drinking water [11] (Figure 1).

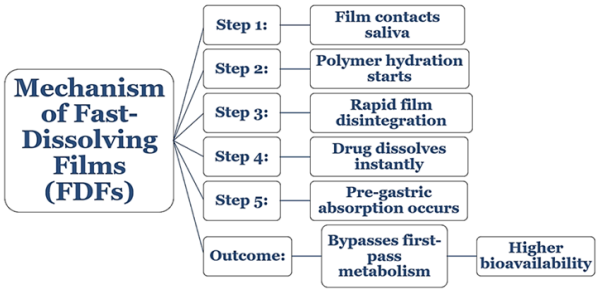

Figure 1. Mechanism of Fast-Dissolving Films.

The use of these systems is very beneficial for kids, elderly, and patients with swallowing difficulties because of their being easy to use and quick to deliver therapeutic action [12].

The basic working principle is polymer hydration and fast film disintegration, which allows pre-gastric absorption and bypassing of hepatic first-pass metabolism thus resulting in better bioavailability [13]. The formulation methods usually consist of making use of hydrophilic film-forming polymers, plasticizers and taste-masking agents in combination to assure the quality of the film in terms of flexibility, stability and the patient's acceptance [11,14].

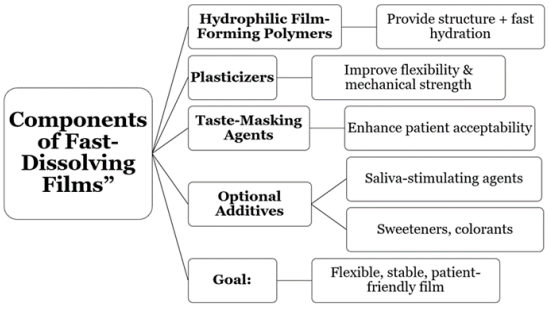

Figure 2. Components of FDFs.

The regulators have pointed out that uniformity of drug content, rapid disintegration time and mechanical integrity are

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quality parameters that are of utmost importance for FDFs. The recognition of these dosage forms by global regulatory bodies is on the rise due to their potentiality in precision dosing as well as their adaptability to local and systemic delivery applications [13,14] (Figure 2).

Effervescent and controlled release tablets

Effervescent tablets unite the therapeutic power and patient comfort by the unique mechanism of dissolution which is based on acid–base reactions that produce carbon dioxide when they meet water [15]. This carbon dioxide production or effervescence increases the rate of dissolution, masking the taste, and improving absorption; thus, they are excellent for the drugs that need fast bioavailability or taste masking [16]. The innovators of the methodology have concentrated on the optimization of the effervescent base ratios, moisture protection, and tablet hardness to prolong the shelf life of the product and to obtain stable performance. The new formulation design has also used new binders and lubricants in a way that enhance compressibility and the dissolution kinetics [15, 16]. In contrast, controlled release formulations direct the way to sustain therapeutic levels by varying the drug release rate over long periods. Such systems are made to last using polymers, coatings, and matrix technologies that can cope with the human body's conditions, thus making the drug less frequent and patient adherence increased [17]. The effervescent and controlled release systems also represent the evolution of customized and patient-centered pharmaceutical design (Figure 3).

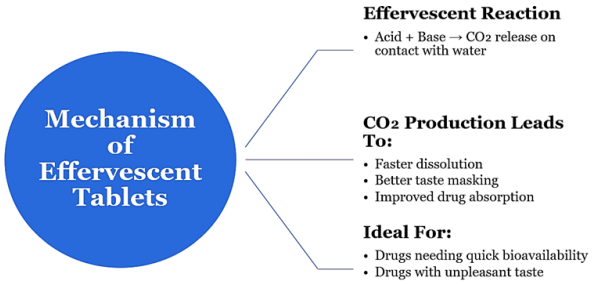

Figure 3. Mechanism of effervescent tablets.

Pulmonary and Nasal Drug Delivery

Pulmonary and nasal drug delivery systems have become hype around their capacity to perform the medical agents' respiratory tract delivery, ensuring a quicker process of both systemic absorption and obtaining the local therapeutic effect. The merging of nanomedicine with aerosol formulations has benefited drug solubility, stability, and deposition efficiency within the lungs and nasal cavity [18]. These nanosystems can accurately target the mucosal tissues and, at the same time, reduce the likelihood of systemic side effects, which in turn leads to a more comfortable patient experience.

Nano-formulations for pulmonary delivery are based on the use of liposomes, solid lipid nanoparticles, and polymeric carriers to achieve controlled release and optimal particle size for deep lung penetration. Overcoming the limitations of inhalation technique that are mostly due to patient factors, formulation has also advanced in terms of engineering, leading to the development of the devices and the drugs that possess both good aerodynamic performance and prolonged residence time in the respiratory tract thus enabling the treatment of chronic respiratory diseases like asthma, COPD, and pulmonary infections to be more efficient [19].

The knowledge gained about inhaled drugs pharmacokinetic has opened the door for the development of predictive frameworks, which include factors like particle deposition, dissolution, and systemic absorption. These models play a vital role in the optimization of inhaler design and dosing regimens for both local and systemic therapies [20].

Nanoscale formulations that use liposomes as the main carrier have significantly widened the range of pulmonary delivery by offering biocompatible and multi-purpose carriers that are able to encapsulate both hydrophilic and lipophilic drugs. Their capability of augmenting mucosal adhesion and controlling release has resulted in higher therapeutic efficiency and lower dosing [21, 22]. All this because of newly introduced technologies in pulmonary and nasal nanocarrier systems has changed the whole respiratory drug industry, making it more convenient and effective for patients and more non-invasive as well.

Lipid-Based and Nanocarrier Systems

Liposomes

Liposomes, which are vesicular carriers made of phospholipids, can encapsulate therapeutic agents in either aqueous or lipid compartments and thus, they provide a biocompatible and versatile platform for drug delivery. Due to their vesicular structure, both hydrophilic and lipophilic drugs can be encapsulated, whilst composition, which comprises typically phosphatidylcholine, cholesterol, and stabilizers, can directly affect the encapsulation efficiency and release kinetics [23].

Regulatory advancement and commercialization of liposomal formulations have been highlighted in the recent studies along with the numerous approved products which have shown better pharmacokinetics, less toxicity, and improved therapeutic targeting [24]. Liposomes have earned a place in the center stage of modern pharmacotherapy due to their capability of protecting unstable drugs from degradation and giving rise to prolonged or stimuli-responsive release [24, 25].

Drug delivery systems based on liposomes have been recognized as an essential strategy in cancer research that allows targeted therapy with reduced system toxicity, and tumor accumulation via the enhanced permeability and retention (EPR) effect [25]. Advanced formulations like PEGylated and ligand-modified liposomes go further in enhancing tumor selectivity and improving therapeutic outcomes. The combination of liposomal and lipid nanoparticle technologies continues to create a revolutionary change in oncological treatments by offering biocompatibility along with precision delivery [26, 27].

Other lipid-based nanosystems

Modern lipid-based nanocarriers have surpassed the classical liposomes in the forms of solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), and lipid–polymer hybrids, mainly because of their improved stability, scalability, and drug-loading capabilities [2]. The combination of lipid biocompatibility with nanoscale delivery precision led to the offer of controlled and site-specific drug release for the whole range of therapeutic agents [5].

Formulation science has made great strides recently, which resulted in optimally combining various lipid matrix components and surfactant selection for achieving tunable release profiles, better bioavailability, and excellent pharmacokinetic behavior [6]. Moreover, the understanding of the mechanism of drug absorption and distribution from inhaled or orally administered

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lipid nanocarriers has been aided using predictive pharmacokinetic models, which also support their transition into clinical practice [20]. In combination, these nanosystems are the next frontier of lipid-based therapeutics, as they can connect the traditional delivery approaches with the emerging of nanotechnological innovations.

Emerging and Targeted Drug Delivery Technology

The past few years have seen incredible advancements in self-powered and targeted drug delivery systems that are able to enhance precision of treatment and penetrate biological barriers. The self-powered systems, which are equipped with micro- and nano-scale energy harvesters, can autonomously release the drug through internal physiological gradients [4]. Such innovations can create instant responsiveness, less invasiveness, and more patient cooperation, especially during treatment of diseases occurring over a long period of time or in specific locations.

At the same time, systems for controlled and targeted delivery have been reached through advanced formulation and nanotechnology integration. The responsive carriers that are capable of the selective release of drugs in the disease site are being researched more in the current studies [5]. The collaboration between the characteristics of physicochemical carriers and biological environments allows for a precise control over pharmacokinetic and pharmacodynamic behaviors, thus opening a new sphere in patient-specific medicine.

Besides all these, excipients-based drug delivery systems have also shown the promise for the development of self-activating release mechanisms. These formulations, using the combined effect of fluid dynamics and gas evolution, undergo quick disintegration and enhanced drug dispersion, thus resulting in faster onset and better absorption [15]. All these new technologies together are set to change the drug delivery science radically where self-activation, targeting, and personalization come together to reshape the therapeutic landscape (Table 2).

Table 2. Emerging and targeted drug delivery technologies.

Innovations	Description	Advantages	References
Self-Powered Drug Delivery Systems	These systems use micro- and nano-scale energy harvesters that autonomously release drugs using internal physiological gradients.	Autonomous drug release, high precision, minimal invasiveness, improved patient cooperation, effective for chronic/localized diseases.	[4]
Responsive & Targeted Nanocarriers	Nanotechnology-based systems engineered to release drugs selectively at disease sites through stimuli such as pH, enzymes, or temperature.	Improved targeting, reduced systemic toxicity, precise pharmacokinetic and pharmacodynamic control, enhanced patient-specific therapy.	[5]
Excipients-Based Self-Activating Systems	Formulations that utilize fluid dynamics and gas evolution to promote rapid disintegration and drug dispersion.	Faster onset of action, improved absorption, enhanced drug distribution.	[15]
Overall Technological Impact	Combination of self-powered, responsive, and excipient-based technologies transforming the future of drug delivery.	Integration of personalization, high precision, and intelligent release mechanisms shaping next-gen therapeutics.	[4,5,15]

Conclusion

The whole sphere of drug delivery technologies is in a state of flux, and the pharmaceutical industry has been mostly influenced by the changes that this one has brought about. The very modern forms of oral medication can be named chewable, fast-dissolving, and effervescent tablets. They have all opened the ways of patients' compliance and the onset of effects very rapidly, consequently, the therapeutic effect through the optimized formulation science has been enhanced.

The routes of pulmonary and nasal administration not only increased the range of therapeutic application but localized the treatment of respiratory disorders and the systemic delivery of macromolecules by means of improved bioavailability and reduced first-pass metabolism. The nano-formulations in these systems have successfully and very accurately targeted the delivery of the drug, meticulously controlled its release and even increased the stability of the drug thus bridging the gap between drug design and medical application.

In drug delivery, the most versatile lipid systems that have been enclosing, protecting and finally targeting the release of biopharmaceuticals are liposome and nanostructured lipid carriers among the strategies. Their application in cancer treatment, managing chronic diseases and personalizing medication is indicative of their increased importance in hospital settings. The forthcoming self-powered and targeted methods represent the next stage in the evolution bringing in autonomous, responsive, and intelligent mechanisms capable of interacting with the biological environment dynamically.

All these innovations, directly or indirectly, are driven by the same goal to increase the therapeutic effect, reduce the side effects and make the drugs more convenient for the patients. Combination of nanotechnology, materials science, and biopharmaceutics will still need drug delivery to be more precise, adaptive, and efficient thus opening new vistas not only for the future of precision therapeutics but also for worldwide healthcare progress.

Disclosure Statement

The author does not have conflict of interest in this research.

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